Since the discovery of high-$T_c$ superconductivity in iron-based materials, a tremendous amount of research has been performed on its properties. Following the discovery in LaFeAs(O,F) with $T_c = 26$ K, superconductivity was found in many materials with related crystal structures that commonly possess iron-pnictide or iron-chalcogenide layers. Like in the cuprates and heavy fermion metals superconductivity of the iron-based compounds has an intimate relation to magnetism. The maximal $T_c$ is found in the vicinity of the extrapolated point where spin-density-wave (SDW) order of the Fe 3$d$ magnetic moment is suppressed by pressure or doping.

The AFe$_2$As$_2$ (A = Ba, Sr, Ca, or Eu) (“122”) systems are prototype iron pnictide materials, since clean, large, and homogeneous single crystals are available and various ways of tuning towards superconductivity have been reported. EuFe$_2$As$_2$ is unique among them because it carries a local magnetic moment due to the divalent Eu atoms. It exhibits a combined transition of structural and SDW order of Fe magnetic moments at $T_0 = 190$ K and subsequently Eu 4$f$ moments order below $T_\theta = 19$ K into a canted antiferromagnetic (AF) state. This state is characterized by a ferromagnetic (FM) alignment of the moments along the orthorhombic $a$ axis with AF coupling along $c$. Interestingly, the magnetic susceptibility above $T_\theta$, which is dominated by the fluctuating Eu$^{2+}$ moments, displays a Curie-Weiss law, $\chi = \chi_0 + C/(T - \theta)$, with positive Weiss temperature, $\theta \sim 20$ K, despite the AF ground state. Indeed, the AF ground state could easily be switched to a FM state in small in-plane fields of order 1 T. These observations suggest that the Eu system is close to a FM instability. Either the application of hydrostatic pressure to EuFe$_2$As$_2$ or the P substitution on the As site in EuFe$_2$(As$_{1-x}$P$_x$)$_2$, which induces chemical pressure, suppresses the $T_0$ transition and induces superconductivity. The superconducting (SC) transition reaches up to 30 K at the optimal pressure and P substitution around 2.8 GPa and $x \approx 0.2$, respectively. The magnetic ordering of Eu moments also changes its character as P is substituted. At low $x$ a canting of the moments along the $c$ axis develops, which grows with increasing $x$, giving rise to a FM hysteresis in magnetization along the $c$ axis, while the system still displays an AF ground state. At $x > 0.23$ the Eu ordering switches to FM. One of the important and controversially discussed issues in EuFe$_2$(As$_{1-x}$P$_x$)$_2$ is the interplay between superconductivity and Eu-FM ordering. In the past, Ren et al. reported a SC transition at 26 K, followed by FM ordering of Eu magnetic moments at 20 K on polycrystalline samples of EuFe$_2$(As$_{0.7}$P$_{0.3}$)$_2$ and discussed a bulk coexistence of both phenomena, which would have important consequences on the SC order parameter. Subsequent magnetic Compton scattering experiments on similar polycrystalline material indicated competition between the two phenomena. We have previously reported the phase diagram for single-crystalline EuFe$_2$(As$_{1-x}$P$_x$)$_2$. In contrast to the report on polycrystals, we found that single crystals with $x \geq 0.26$ are lacking bulk superconductivity. In this study we have carefully investigated the homogeneity of the P content by energy dispersive x-ray (EDX) microprobe analysis, since already a small inhomogeneity in the P content could lead to a seeming coexistence of SC and FM order, due to contributions from different volume fractions. Thus, any small inhomogeneity or deviation between the nominal and actual composition may explain the discrepancy to the experiments on polycrystals. However, three more recent studies on polycrystals also claim a much wider SC region for $0.2 \leq x \leq 0.4$ and concluded a bulk coexistence of superconductivity and FM order. Since this issue may sensitively depend on inhomogeneities and sample quality which could vary with different P substitutions, we decided to perform detailed hydrostatic pressure experiments on two selected well-characterized P-substituted single crystals.

As shown below, we can perfectly map the hydrostatic pressure results to our previously determined phase diagram for single-crystalline EuFe$_2$(As$_{1-x}$P$_x$)$_2$. In particular, we verify the peculiar extremely narrow existence range of bulk superconductivity and its suppression at the concentration $x = 0.23$ for which Eu magnetic order switches to FM. Additionally, we can relate this transition to a change of the electronic structure due to a Lifshitz transition, that meanwhile has been established by angular-resolved photoemission spectroscopy (ARPES), as well as thermopower measurements.

Single crystals of EuFe$_2$(As$_{1-x}$P$_x$)$_2$ were grown by the FeAs self-flux method. The homogeneity and actual composition of the two samples with $x = 0.13$ and $x = 0.18$ was confirmed within $\Delta x = 0.01$ error by EDX microprobe analysis on several points of cleaved surfaces. Powder x-ray analysis displays a compression of the unit cell volume, related to the chemical pressure effect of P substitution.
The temperature dependence of the electrical resistivity under hydrostatic pressure was measured by a standard four-probe method with the current flowing in the tetragonal basal plane. The measurements were performed from room temperature down to 4.2 K and under hydrostatic pressure up to ∼1.5 GPa by utilizing a CuBe piston-cylinder pressure cell. Daphne oil was used as a pressure-transmitting medium. The applied pressure was carefully determined by detecting the change of structural (T_s) and SDW (T_{SDW}) ordering. The inset of Fig. 1 shows a hump, which is a signature of the Eu magnetic local moments. In previous hydrostatic pressure experiments on EuFe_2(As_{0.82}P_{0.18})_2, cf. Fig. 2. This sample is a bulk superconductor at ambient pressure, confirmed by Meißner effect and specific-heat measurements, and displays a sharp and complete resistive SC transition at 22 K, i.e., slightly below the maximal T_c of 30 K found previously for a x = 0.2 single crystal. Upon increasing the hydrostatic pressure, T_c does not increase, as one might have expected from the phase diagram of EuFe_2(As_{1−x}P_x)_2. Rather the SC transition becomes incomplete (cf. the inset), shifts towards lower temperatures, and is suppressed at a pressure of 0.87 GPa. The incomplete SC transition also displays a signature at the ordering of Eu^{2+} local moments. In previous hydrostatic pressure experiments on EuFe_2As_2, similar behavior has been found at pressures slightly below or above the pressure range of bulk superconductivity. The data thus indicate that single-crystalline EuFe_2(As_{0.82}P_{0.18})_2 is located just at the border of bulk superconductivity, which disappears at very low pressure.

In order to obtain a quantitative comparison between the pressure and P substitution, we use the bulk modulus B = 82.9 ± 1.4 GPa of BaFe_2As_2, determined in the orthorhombic state at 33 K (Ref. 25), and the change of the lattice constants in EuFe_2(As_{1−x}P_x)_2. Using these data, 0.61 GPa corresponds to 5% of P substitution. Consequently, EuFe_2(As_{0.87}P_{0.13})_2 at signal in the magnetic susceptibility. This signature is related to a very small SC volume fraction, likely due to some very small inhomogeneity, which could not be detected within the resolution of x-ray diffraction and EDX. With increasing pressure, the SC signal is getting more pronounced, reaching ρ = 0 at the highest pressure, indicating an increase of the SC volume fraction. At low temperatures, the resistivity also shows a hump, which is a signature of the Eu magnetic ordering.

We have performed similar hydrostatic pressure experiments on EuFe_2(As_{0.82}P_{0.18})_2; cf. Fig. 2. This sample is a bulk superconductor at ambient pressure, confirmed by Meißner effect and specific-heat measurements, and displays a sharp and complete resistive SC transition at 22 K, i.e., slightly below the maximal T_c of 30 K found previously for a x = 0.2 single crystal. Upon increasing the hydrostatic pressure, T_c does not increase, as one might have expected from the phase diagram of EuFe_2(As_{1−x}P_x)_2. Rather the SC transition becomes incomplete (cf. the inset), shifts towards lower temperatures, and is suppressed at a pressure of 0.87 GPa. The incomplete SC transition also displays a signature at the ordering of Eu^{2+} local moments. In previous hydrostatic pressure experiments on EuFe_2As_2, similar behavior has been found at pressures slightly below or above the pressure range of bulk superconductivity. The data thus indicate that single-crystalline EuFe_2(As_{0.82}P_{0.18})_2 is located just at the border of bulk superconductivity, which disappears at very low pressure.

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a pressure of 0.61 GPa corresponds to \( x = 0.18 \) at ambient pressure. Indeed both data sets display similar curvature above the SC transition (cf. Figs. 1 and 2), and increasing hydrostatic pressure for both concentrations leads to a more linear temperature dependence of \( \rho(T) \). We fitted the resistivity data between 25 and 100 K to a simple power law form

\[
\rho(T) = \rho_0 + A T^n
\]

with chemical pressure has been found. Importantly, the inner hole-like Fermi surface near the \( \Gamma \) point shrinks to zero at \( x \approx 0.23 \). Indeed, TEP has found indication for a Lifshitz transition near this concentration, from a nonmonotonic evolution of \( S(x) \) at constant temperature. Such a change of the electronic configuration may also influence the Eu\(^{2+}\) magnetic ordering, since density-functional-theory-based calculations have found almost similar ground-state energies for the AF and FM configurations using the room-temperature lattice constants in this concentration range. Since the Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange coupling between the Eu\(^{2+}\) local moments is oscillatory with the distance, starting with a FM coupling at low distances, the general trend towards ferromagnetism under chemical pressure is expected. Interestingly, by using a minimal multiband model, it has recently been shown that the Fermi surface nesting properties at the Fermi level have been found. Importantly, the inner hole-like Fermi surface near the \( \Gamma \) point shrinks to zero at \( x \approx 0.23 \). Indeed, TEP has found indication for a Lifshitz transition near this concentration, from a nonmonotonic evolution of \( S(x) \) at constant temperature. Such a change of the electronic configuration may also influence the Eu\(^{2+}\) magnetic ordering, since density-functional-theory-based calculations have found almost similar ground-state energies for the AF and FM configurations using the room-temperature lattice constants in this concentration range. Since the Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange coupling between the Eu\(^{2+}\) local moments is oscillatory with the distance, starting with a FM coupling at low distances, the general trend towards ferromagnetism under chemical pressure is expected. Interestingly, by using a minimal multiband model, it has recently been shown that the Fermi surface nesting properties at the Fermi level have been found. Importantly, the inner hole-like Fermi surface near the \( \Gamma \) point shrinks to zero at \( x \approx 0.23 \). Indeed, TEP has found indication for a Lifshitz transition near this concentration, from a nonmonotonic evolution of \( S(x) \) at constant temperature. Such a change of the electronic configuration may also influence the Eu\(^{2+}\) magnetic ordering, since density-functional-theory-based calculations have found almost similar ground-state energies for the AF and FM configurations using the room-temperature lattice constants in this concentration range. Since the Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange coupling between the Eu\(^{2+}\) local moments is oscillatory with the distance, starting with a FM coupling at low distances, the general trend towards ferromagnetism under chemical pressure is expected. Interestingly, by using a minimal multiband model, it has recently been shown that the Fermi surface nesting properties at the Fermi level have been found. Importantly, the inner hole-like Fermi surface near the \( \Gamma \) point shrinks to zero at \( x \approx 0.23 \). Indeed, TEP has found indication for a Lifshitz transition near this concentration, from a nonmonotonic evolution of \( S(x) \) at constant temperature. Such a change of the electronic configuration may also influence the Eu\(^{2+}\) magnetic ordering, since density-functional-theory-based calculations have found almost similar ground-state energies for the AF and FM configurations using the room-temperature lattice constants in this concentration range. Since the Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange coupling between the Eu\(^{2+}\) local moments is oscillatory with the distance, starting with a FM coupling at low distances, the general trend towards ferromagnetism under chemical pressure is expected.
crystals. Using the reported value of the bulk modulus and the measured change of the lattice constants with $x$, we could quantitatively map the hydrostatic to the chemical pressure in this system. Our pressure experiments confirm the extremely narrow SC dome in this system, which is very different from this system. Our pressure experiments confirm the extremely narrow SC dome in this system, which is very different from this system.  

The change of the electronic structure together with the structural change most likely modifies the Eu-RKKY interaction such that the Eu magnetism switches from AF to FM ordering. Since FM order is incompatible with superconductivity, this explains the peculiar phase diagram of EuFe$_2$(As$_{1-x}$P$_x$)$_2$, where a SC phase only exists in a very narrow regime.

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